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(54) **Method of and apparatus for accurately determining the azimuth by measuring a plurality of phase shifts**

(57) A method of determining the azimuth α of a transponder 5 relative to a radar system 1 which transmits a frequency F, which frequency is a linear function of time, which system comprises two receiving antennas 3, 4, disposed at a distance d from each other and supplies two beat signals Fb_1 and Fb_2, which form the difference between the transmitted wave and each of the two echo waves received from the transponder. In accordance with the invention the phase shift γ_0 between Fb_1 and Fb_2 for a first point (Fb_1, t_1) and the phase shift γ'_0 for a second point (F_2, t_2) of the curve F(t) is measured, an approximate value of the overall phase shift γ between Fb_1 and Fb_2 is calculated, which is $\gamma = \gamma_0 + 2k\pi$, from F_1, F_2 and $\gamma'_0 - \gamma_0$, the integral value of k is derived from γ, γ_0 the sign of γ and of $\gamma'_0 - \gamma_0$ is determined, the exact value of γ is calculated from k and γ_0, and the value of α is calculated from the value of its sine derived from the values F_1, d and the exact value of γ.

The invention is used for accurately determining the angular position of a transponder or a passive reflector.


FIG.1
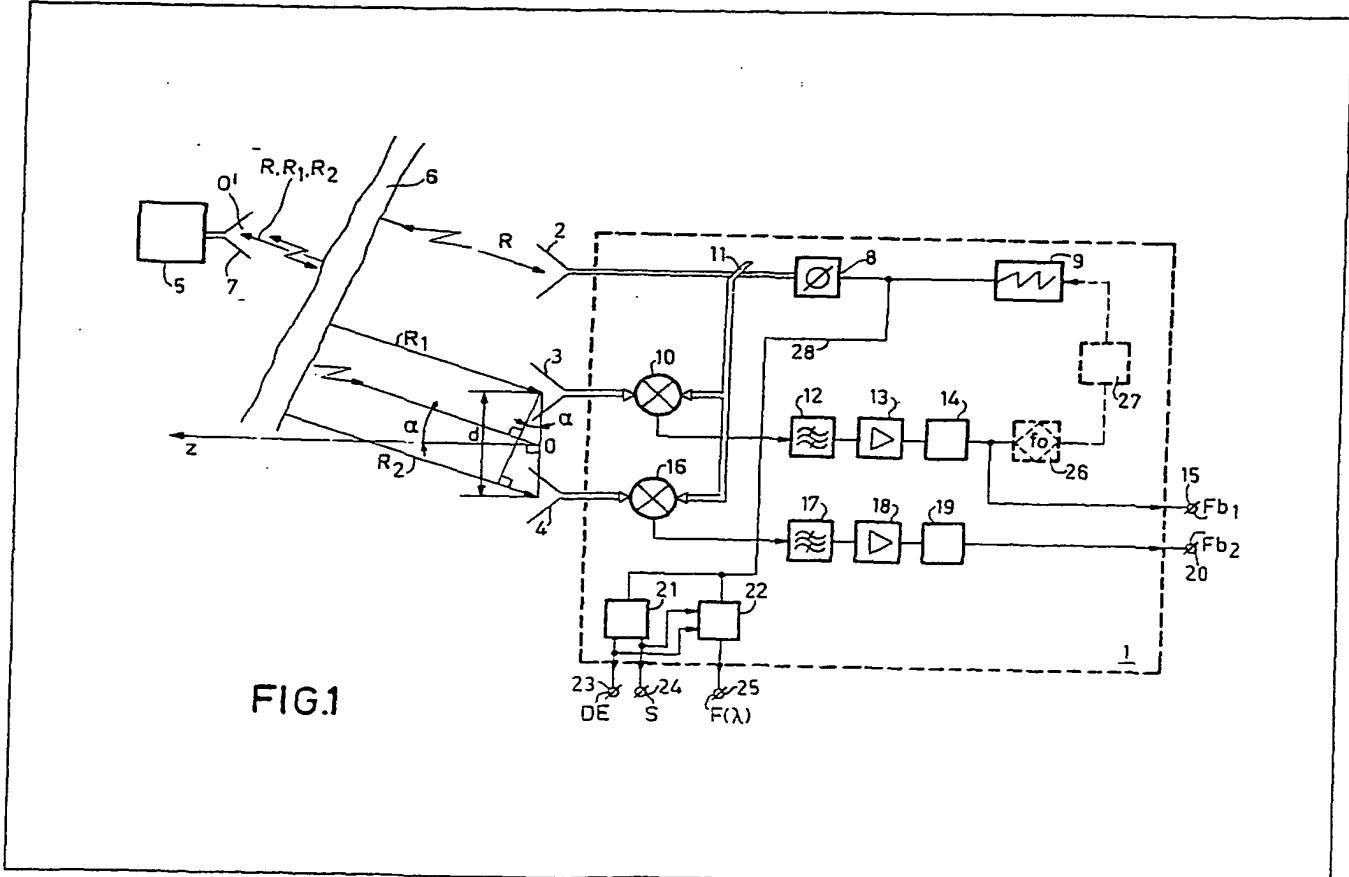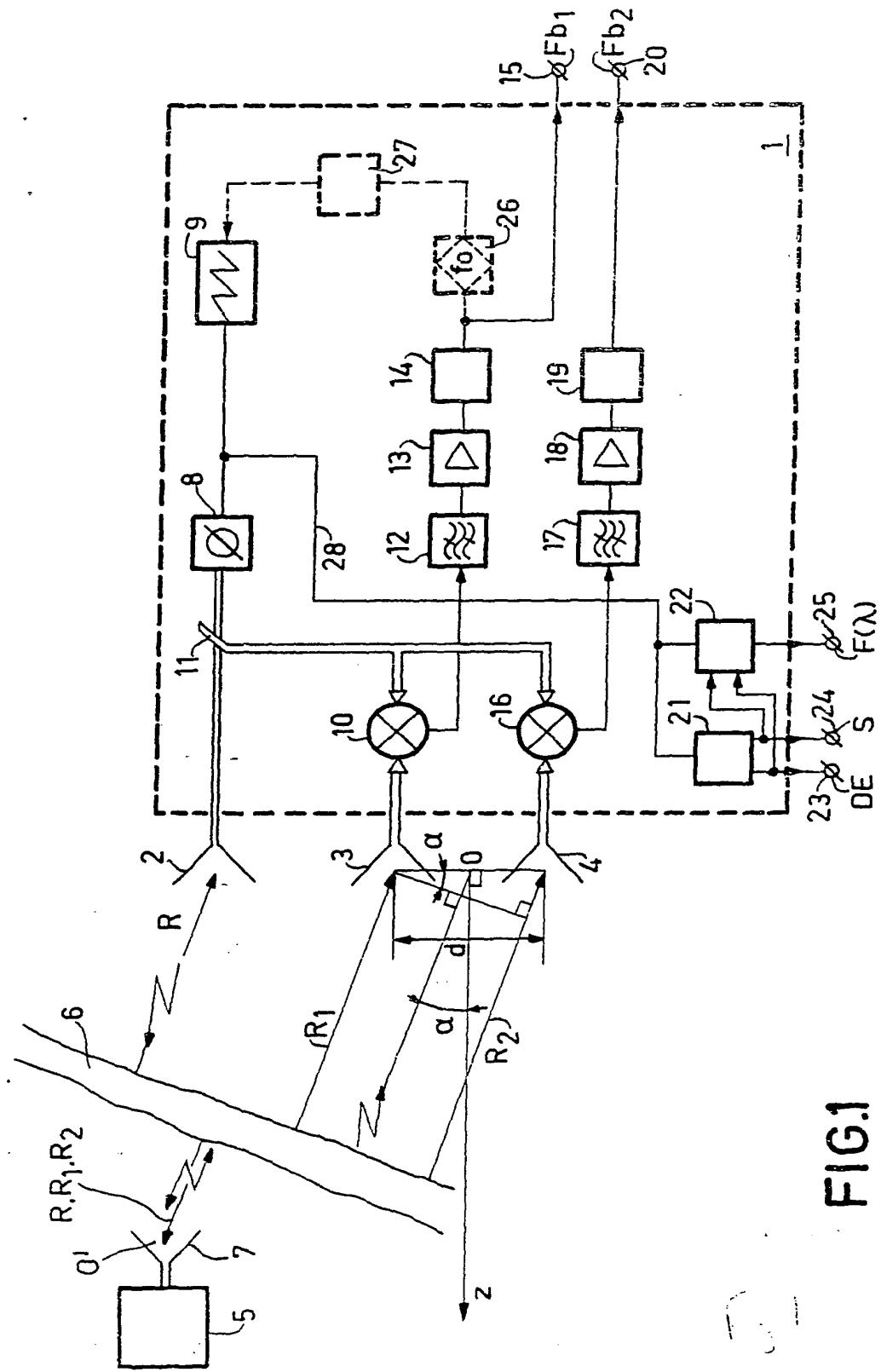
FIG.1
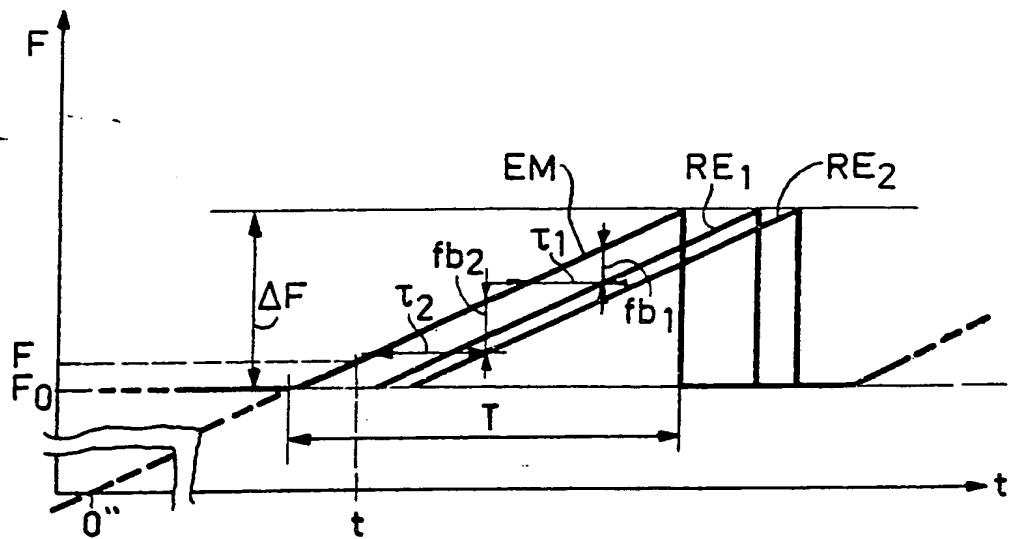
FIG.2
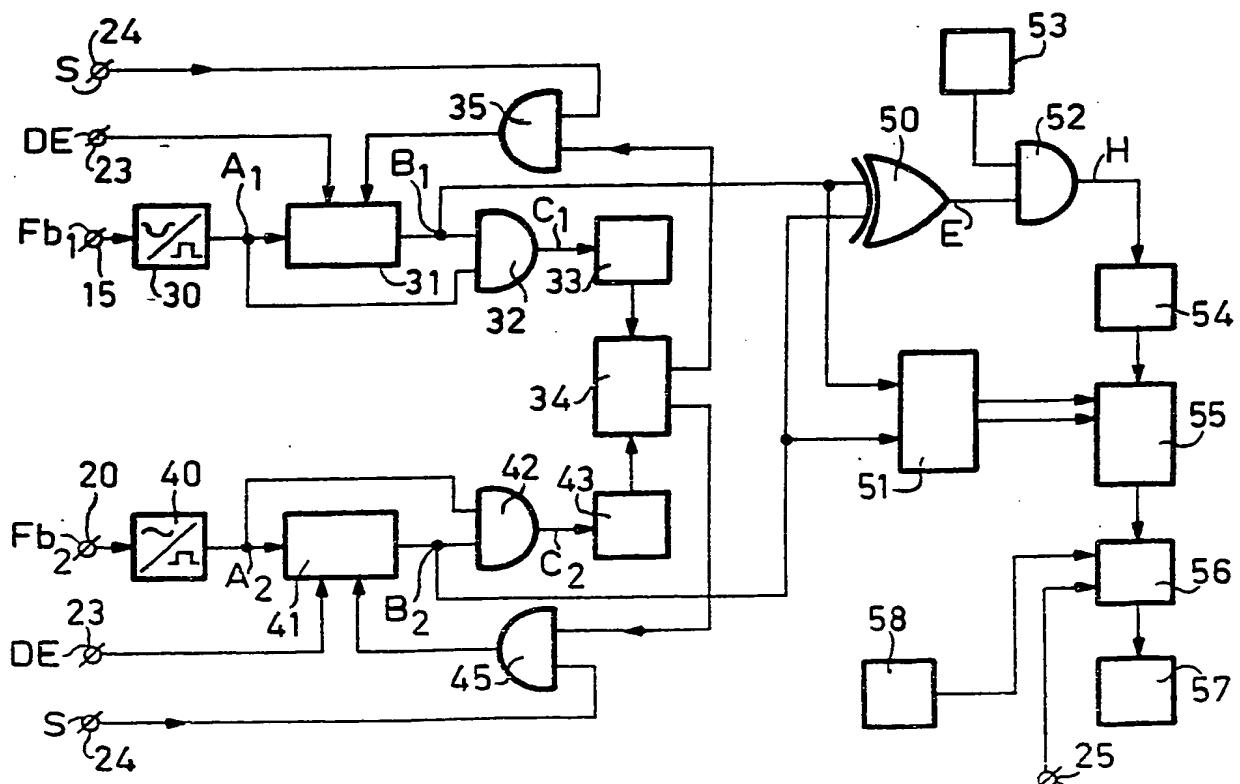
FIG.3
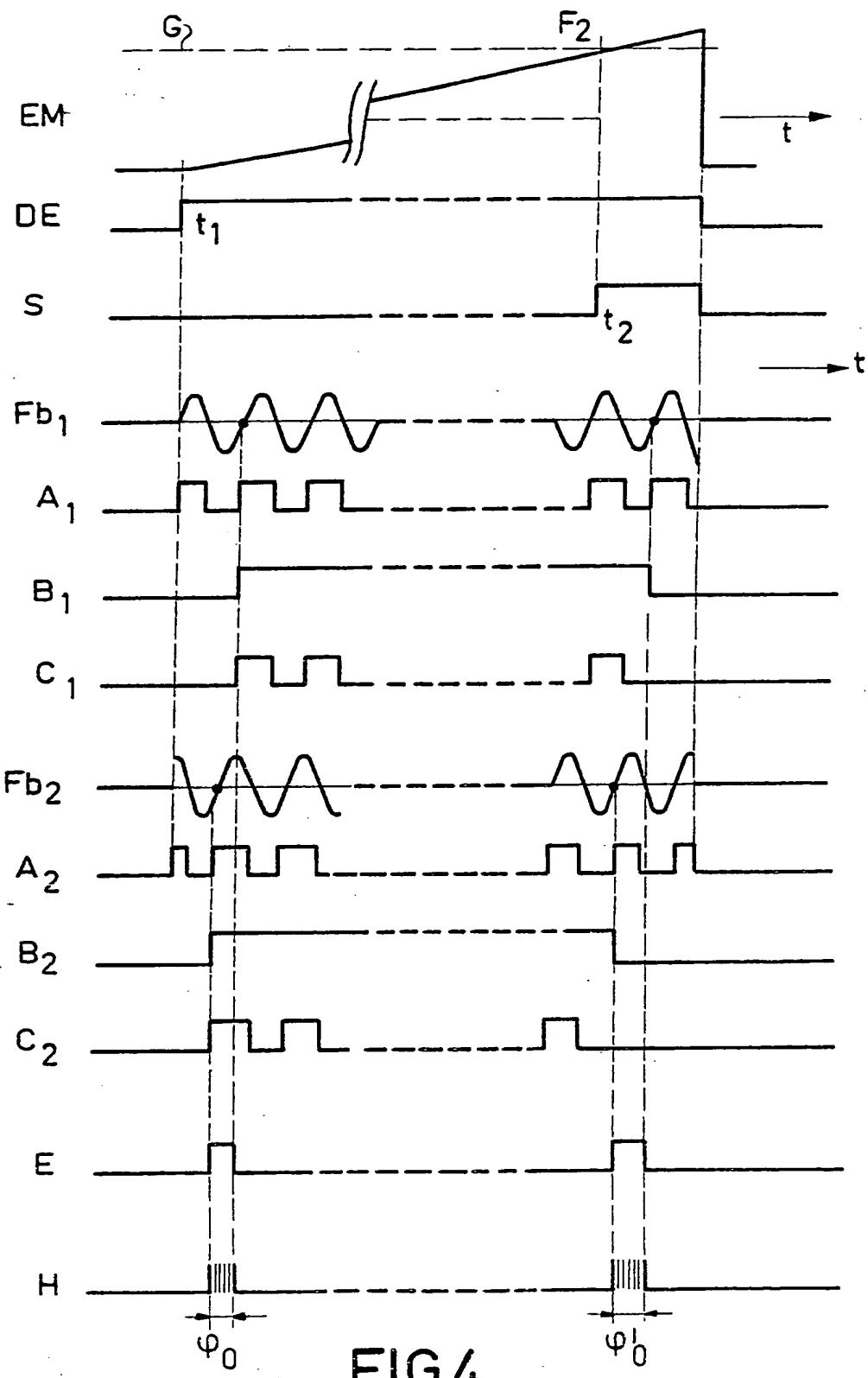
FIG.4

SPECIFICATION

Method of an apparatus for accurately det rmining
the azimuth by measuring a plurality of phase shifts

5   The invention relates to a method of determining
the azimuth α of a radiowave transponder relative to
a radar system, which system transmits a wave
whose frequency F is a linear function of time, said
10 radar system comprising a transmitting antenna and
two receiving antennas, which are located at a dis-
tance d from each other, and supplying two beat
signals Fb_1 and Fb_2 having a frequency fb_1 and fb_2
respectively, which are obtained by mixing the
15 transmitted wave and the echo wave received from
said transponder on each of the two receiving
antennas.
    The invention also relates to an apparatus for
measuring the azimuth α using the said method,
20 which apparatus forms part of a radar system which
transmits a high frequency continuous wave, which
is frequency modulated with a sawtooth having a
constant frequency sweep ΔF and a duration T, and
which simultaneously receives the previously
25 transmitted wave which is reflected by a transpon-
der, said radar system supplying a signal Fb_1 of a
first beat frequency fb_1, obtained by mixing the
transmitted signal of the instantaneous frequency F
and the signal received on a first receiving antenna,
30 and a signal Fb_2 of a second beat frequency fb_2,
obtained by mixing said transmitted signal of the
frequency F and a signal received on a second
receiving antenna, the reference direction for
measuring the azimuth α of said transponder being
35 the mid-perpendicular to the line section of the
length t at whose ends said receiving antennas are
located.
    The azimuth angle α to be determined is the angle
between a predetermined direction, for example a
40 reference axis associated with the apparatus for
measuring α, and an axis which extends from the
measuring apparatus to a target whose angular loca-
tion is to be determined. Suitably, the measuring sta-
tion is located on the ground, the measuring
45 apparatus comprising a radar interrogator, and the
target is an aircraft equipped with a transponder.
The measuring station may alternatively be an air-
craft. In practice, the angle α to be determined is
suitably the angle between the mid-perpendicular
50 plane to the receiving antennas of said radar system
and the axis between the radar system and the
target. On the other hand, the transponder associ-
ated with the target may be a simple passive reflec-
tor, in so far that it is isolated in the space surround-
55 ing it.
    The apparatus used for carrying out the invention
may, as far as the radar interrogator is concerned,
for example be of the type known from French
Patent Specification no. 1,557,670. The radar system
60 moreover comprises a second receiving antenna by
means of which a second beat signal Fb_2 of the fre-
quency fb_2 is obtained by mixing the transmitted
wave and the wave received by said second receiv-
ing antenna in a second mixer. Such a radar system
65 serves as a distance measuring apparatus and to this

end it comprises a control loop which maintains the
first beat signal Fb_1 at a substantially constant fre-
quency fb_1 as said distance varies. This results in a
variation of the duration of th transmitted sawtooth
70 as a linear function of the distance for a constant
frequency sweep Δ f of the sawtooth.
    It is to be noted that the invention is not limited to
this type of apparatus. It equally applies to a radar
system which transmits a sawtooth of constant fre-
75 quency, duration and frequency sweep and which
supplies two beat signals Fb_1 and Fb_2 obtained by
mixing of the transmitted wave and the echo wave
received from the transponder on the receiving
antenna.
80   The transponder used is for example of the type
described in French Patent Specification 2,343,258,
in particular with reference to Figures 9 and 10 of
said Specification, by means of which the azimuth of
the target can be calculated up to distances greater
85 than 100 km.
    By means of the two distance measuring
apparatus of the type described in the said French
Patent 'Specification 1,557,670, having a common
transmitting antenna and each having on receiving
90 antenna, the azimuth can be determined in known
manner from two distance measured by triangula-
tion using the formula:

$$\sin \alpha = (R_1 - R_2)/d$$

95
in which:
d   is the (fixed) distance between the receiving
    antennas
R_1 is the distance between the transponder and one
100   receiving antenna
R_2 is the distance between the transponder and the
    other receiving antenna.
The principle of determining α is described in more
detail in the previously mentioned French Patent
105 Specification 2,343,258.
    When α is thus determined this has the drawback
that at least one distance measuring apparatus is
necessary (by alternately switching the control loop
from one receiving antenna to the other – in which
110 case the frequencies fb_1 and fb_2 are equal) and that
the measurement of α is not very accurate because
of the length of the signal-processing chain neces-
sary to enable the distances R_1 and R_2 and their dif-
ference to be determined, which leads to an accumu-
115 lation of the absolute errors produced by the various
signal-processing elements, the cumulative error
increasing as the distance R increases.
    It is also possible to determine the angle α by
means of the formula:
120

$$\sin \alpha = cT (fb_1 - fb_2)/\Delta Fd$$

c being the velocity of propagation of an elec-
tromagnetic wave.
125   Such a method of determining α by measure-
ments of T, fb_1 and fb_2 has the same drawbacks as
described in the foregoing.
    It is an object of the invention to obtain a compara-
tively high accuracy for α, for example of some hun-
130 dredths of a degree, using simple radar equipment,

said accuracy being of the same order of magnitude
as that obtained by means of an aircraft landing
radar system (ILS sytem). More specifically, it is the
object of the invention to obtain this high accuracy
5 by means of two antennas only, whilst in conven-
tional angle measuring systems this is achieved by
means of a large number of antennas (interferomet-
ers with a plurality of antennas).
   This object is achieved in that, according to the
10 invention, the method defined in the opening para-
graph at least comprises the following steps:
   — The algebraic measurement of the phase shift φ_0
      between the signals Fb_1 and Fb_2 and the measure-
      ment of the frequency F_1 at a predetermined, arbit-
15   rarily chosen first instant t_1,
   — The algebraic measurement of the phase shift φ'_0
      between the signals Fb_1 and Fb_2 and the measure-
      ment of the frequency F_2 at a second arbitrarily
      chosen instant t_2, $\varphi'_0 - \varphi_0$ being such that the
20   number of sinewave periods of fb_1 and fb_2 between
      the two instants t_1 and t_2 is substantially the same,
   — The calculation of a relative overall phase variation
      $\Delta \varphi$ which may be greater than 2π between the
      instants t_1 and t_2, by determining the difference
25   between φ'_0 and φ_0,
   — The approximated calculation of φ, which is the
      overall phase shift between the signals Fb_1 and Fb_2
      at said first instant t_1, to be reckoned from the fre-
      quency F at which said overall phase shift is zero,
30   as a function of F_1, F_2 and the value of $\Delta \varphi$ found in
      the preceding step, that is $\varphi \Delta \varphi$,
   — The determination of the maximum angle $2k\pi$, k
      being a positive integer which is actually contained
      in the angle φ, from φ_0, $\varphi \Delta \varphi$ found in the preced-
35   ing step and of the respective signs of φ_0 and of Δ
      φ,
   — Making φ identical to the sum: $\varphi_0 + 2k\pi$ or $\varphi_0 - 2k$
      π depending on the respective signs of φ_0 and of Δ
      φ,
40 — The calculation of $\sin \alpha$ from the values of F_1, k and
      the exact value of φ found in the preceding step,
   — The calculation of α from the value of $\sin \alpha$
      obtained in the preceding step,
   — The display of the value of α found in the preceding
45   step.
   Similarly, in order to obtain a high accuracy for α,
the apparatus defined in the introduction is charac-
terized in that it comprises:
   — First means for shaping said signals Fb_1, Fb_2 of the
50   frequency fb_1 and fb_2 so to obtain squarewave
      signals of the same phase and the same frequency,
   — Second means for measuring the phase shift φ_0
      between the squarewave signals of frequency fb_1
      and fb_2, as well as the frequency F for at least one
55   point of said sawtooth,
   — Third means for determining at least two trains of
      squarewave signals having the same number of
      periods and whose starting points differ by at least
      one period,
60 — Fourth means for measuring the overall relative
      phase variation $\Delta \varphi$ between the beginning, at the
      instant t_1 for a frequency F_1, and the end, at the
      instant t_2 for a frequency F_2, of said trains of
      squarewave signals,
65 — Fifth means for calculating the angle α from the

values of F_1, F_2, d, φ_0 and $\Delta \varphi$ and for displaying
said angle.
   By means of a simple formula, mentioned in the
detailed description, it is possible to calculate the
70 value of $\sin \alpha$ for a given point of the sawtooth from
the value φ of the overall phase shift between Fb_1
and Fb_2 with the required accuracy. The value φ_0
measured for this point of the sawtooth only repres-
ents the portion of φ which is smaller than 2π.
75   The basic concept of the invention is to determine
the angle $2k\pi$ which, when added to φ_0, yields the
angle φ. This is possible by measuring the phase
shift φ'_0 for at least a second point of sawtooth. Thus,
if the phase shifts φ_0, φ'_0 are measured with an accu-
80 racy of the order of, for example, $1°$, that is a relative
error of the order of 0.5%, it is possible to obtain the
angle φ with a much higher relative accuracy.
Indeed, the overall phase shift between Fb_1 and Fb_2
is obtained with a relative accuracy of the order of $1°$
85 in several thousands of degrees. This high accuracy
is then also obtained for α.
   The following description with reference to the
accompanying drawings, given by way of example,
enables the invention to be more fully understood.
90 Corresponding elements bear the same reference
numerals.
   Figure 1 is the simplified block diagram of a radar
system which simultaneously transmits and receives
a high frequency continuous wave, which is
95 frequency-modulated as a sawtooth and which pro-
vides the signals necessary for carrying out the
invention.
   Figure 2 represents the frequency variation of the
transmitted and received signals as a function of
100 time.
   Figure 3 is the block diagram of an embodiment of
the invention.
   Figure 4 is a time diagram illustrating the opera-
tion of the circuits shown in Figures 1 and 3.
105   Figure 1 represents a radar system 1, which may
be a radio altimeter or a distance measuring
apparatus using high-frequency continuous waves
which are frequency-modulated in accordance with
a sawtooth, and which system comprises a transmit-
110 ting antenna 2 as well as two receiving antennas 3
and 4 situated at a distance d from each other. The
radar system 1 forms part of a system which
moreover comprises a transponder 5, represented at
the left in Figure 1, whose distance 6 from the radar
115 system may exceed 140 km. The transponder 5 suit-
ably comprises a single transmitting/receiving
antenna 7 at o'. In order to ensure that the wave
received from the antenna 2 is returned to the
antennas 3 and 4 of the radar system 1 with suffi-
120 cient power, especially in the case of longer dis-
tances, the transponder 5 is suitably of the type
described in French Patent Specification 2,343,258,
in particular with reference to Figures 9 and 10 of
said Specification, or a transponder of comparable
125 design and performance. This type of transponder
comprises a delay line which provides a delay τ_0 of
microsecond order between the received signal and
the retransmitted signal, an amplifier, and means,
in the form of at least one radio-frequency switch for
130 sampling the received signal at a frequency of the

order of some hundreds of kilohertz. The radar system 1 is adapted to analyze the signals returned to its receiving antennas 3 and 4 by the transponder 5 in order to obtain output signals which, in accordance
5 with the invention, enable the value of the angle α, which is the azimuth angle of the transponder relative to the radar system, to be determined with an accuracy of the order of some hundredths of a degree. In Figure 1 α is the angle between the mid-
10 perpendicular $\overrightarrow{oz}$ to the line (i.e. perpendicular to the mid-point of the line) of length d and with a centre o, which line interconnects the centres of the antennas 3 and 4, and the direction $\overrightarrow{oo}$.
The transmitting section of the radar system 1
15 comprises a voltage-controlled oscillator 8 connected to the transmitting antenna 2, the input of said oscillator receiving the output signal of a saw-tooth generator 9.
The receiving section is constituted by two identical
20 signal processing chains. The first chain comprises a mixing circuit 10, of which the first one of the two inputs is connected to the output of the antenna 3 and whose second input is connected to the output of the oscillator 8 via a coupler 11. An output of the
25 mixing circuit 10 is connected to a cascade of a band-pass filter 12, an amplifier 13 and an amplitude limiter 14. The mixer 10 forms the difference frequency of the transmitted wave and the received wave, yielding a signal Fb_1 of the frequency fb_1 on an
30 output terminal 15, which frequency is the instantaneous difference frequency of the wave transmitted at 2 and the wave received at 3.
Like the first chain, the second chain is constituted by the cascade of the receiving antenna 4, the mixer
35 16, the band-pass filter 17, the amplifier 18 and the amplitude limiter 19, the second input of the mixer 16 also being connected to the coupler 11. The output of the amplitude limiter 19 produces a signal Fb_2 of the frequency fb_2 on its output terminal 20, which
40 frequency is the instantaneous difference of the frequencies of the wave transmitted at 2 and the wave received at 4. Moreover, the radar system 1 comprises two elements 21 and 22 which, suitably via a conductor 28, receive the output voltage of the saw-
45 tooth generator 9. The element 21 is a logic signal generator which produces the signals DE and S on the outputs 23 and 24 and the element 22 produces a signal F (or λ) on a terminal 25, the signals DE and S being also supplied to the element 22. The function
50 of these elements 21 and 22 will be described hereinafter with reference to Figures 3 and 4. Figure 1 also shows a frequency discriminator 26, operating at the central frequency f_0, and an integrator 27, arranged in cascade between the output of the amp-
55 litude limiter 4 and a control input of the sawtooth generator 9. Their presence is optional, which is indicated by the broken lines, and their function will be described hereinafter.
Figure 2 represents frequency curves as a function
60 of time, that is the curve EM for the signals transmitted at 2 and 11 and the curves RE_1 and RE_2 for the envelope of the signals received at 3 and 4.
The curve EM has the form of a symmetrical or asymmetrical sawtooth with a fixed or variable dura-
65 tion T and a frequency sweep ΔF, which is prefer-

ably constant. The frequency F_0 is the frequency at the beginning of the sawtooth. In practice F_0 is of the order of magnitude of GHz and ΔF is of the order of magnitude of ten or some tens of MHz. When the
70 Doppler effect is ignored and the waves received at 3 and 4 are continuous, the curves RE_1 and RE_2 can be derived from the curve EM by a translation parallel to the time axis through an interval τ_1 and τ_2 respectively. Referring now to Figure 1, τ_1 is the time which
75 the wave needs to cover the distance R between the antennas 2 and 7, to pass through the transponder 5 (time τ_0) and to cover the distance R_1 between the antennas 7 and 3 in the other direction, namely:

80 $$\tau_1 = \left[(R + R_1)/c\right] + \tau_0 \tag{1}$$

Similarly:

$$\tau_2 = \left[(R + R_2)/c\right] + \tau_0 \tag{2}$$

85 The respective beat frequencies fb_1 resulting from RE_1 and EM and fb_2 resulting from RE_2 and EM may be represented by the formulas:

90 $$fb_1 = \left[(R + R_1)/c + \tau_0\right] \Delta F/T \tag{3}$$

$$fb_2 = \left[(R + R_2)/c + \tau_0\right] \Delta F/T \tag{4}$$

It is to be noted that RE_1 and RE_2 are only the
95 envelopes of the waves received by the radar system. Indeed, for the given type of transponder which is preferably used, the wave returned by the latter is chopped at the sampling frequency, that is for each sampling cycle of a duration which is typically 2 μs, it
100 is only present on the output of the transponder 7 for approximately 1 μs. It follows that the beat signal of the frequency fb_1 (or fb_2) on the output of the mixer 10 or 16 itself is sampled at the sampling frequency of the transponder, which is of the order of 500 kHz.
105 The function of the band-pass filter 12 or 17 is to recover the beat signal in the form of a sinewave of the frequency fb_1 or fb_2 by eliminating the components of the sampling frequency and multiples thereof from the spectrum of the signal which is
110 received. This is possible if the frequencies fb_1 and fb_2 are smaller than half the sampling frequency, that is, for example 250 kHz (Shannon theorem).
When the sawtooth is constant (T and ΔF constant), the criterion given in the preceding paragraph
115 imposes a limitation on the distance between the radar system and the transponder in view of formulas (3) and (4). In order to remove this limitation, the sampling frequency may be increased (by reducing the duration τ_0 of the transponder) and/or the
120 ratio $\Delta F/T$ may be reduced by influencing the values of ΔF and T in the radar system, in such a way that said distance limit imposed by the sampling frequency becomes greater than the distance limit imposed by the maximum gain of the transponder 7.
125 In a preferred embodiment of the invention one of the beat frequencies fb_1 or fb_2 is maintained substantially equal to the constant frequency f_0 by means of a control loop of the transmitting section of the radar system. In Figure 1 said control loop is constituted
130 by the cascade, arranged between the coupler 11

and a control input of the sawtooth generator 9, of
the mixer 10, the filter 12, the amplifier 13, the amp-
litude limiter 14, the frequency discriminator 26 and
the integrator 27. The output signal of the dis-
5 criminator 26 influences the generator 9 via the
integrator 27 in such a way that the slope of the
sawtooth varies as a function of the distance to the
transponder, whilst the frequency fb_1 is maintained
constant. In this type of distance measuring
10 apparatus, which is for example known from the said
French Patent Specification 1,557,670, the duration T
of the sawtooth is a linear function of the distance
between the transponder and the radar system,
thereby enabling said distance to be measured. The
15 significance of the control loop described in the
foregoing for the invention is to ensure that substan-
tially constant values are obtained for fb_1 and fb_2 (the
value of fb_2 being very close to that of fb_1) indepen-
dently of the distance between the radar system and
20 th transponder, which ensures that the sampling
theorem is complied with. In practice, the frequency
f_o is of the order of some tens of kilohertz, that is, an
order of magnitude smaller than the sampling fre-
quency.
25   Referring now to the left-hand part of Figure 1, the
lines R, R_1 and R_2 which connect the antenna 7 to the
antennas 2, 3 and 4 respectively have such a length
that they may be considered to be parallel in good
approximation. As a result of this, the line perpen-
30 dicular to the line 00' (and to the line sections R_1 and
R_2) from the centre of the antenna 3 makes an angle
α with the line of length d. It follows that:

$$\sin \alpha = (R_2 - R_1)/d \qquad (5)$$

35
On the other hand, subtracting formulas (3) and (4)
from each other yields:

$$fb_2 - fb_1 = \Delta F (R_2 - R_1)/cT \qquad (6)$$

40
The (algebraic) difference $fb_1 - fb_2$ may be expre-
ssed as a number of periods which linearly increase
with time or rather an "overall phase shift" φ, whose
absolute value is greater than 2π, which may be
45 expressed by:

$$\varphi = 2\pi(fb_1 - fb_2) t \qquad (7)$$

when taking a suitable origin for t, that is for each
50 sawtooth the points o" where the line corresponding
to the curve EM in Figure 2 intersects the vertical
axis.
    Formula (7) may be written as follows using for-
mula (6):
55
$$\varphi = 2\pi\Delta Ft (R_1 - R_2)/cT \qquad (8)$$

The expression for the curve F as a function of time
for each sawtooth is then:
60
$$F = \frac{\Delta F}{T} t$$

when taking the same origin o" as above for t. For-
65 mula (8) may then be written as follows:

$$\varphi = 2\pi F (R_1 - R_2)/c \qquad (9)$$

    Combining equations (5) and (9) yields:

70 $$\varphi = 2\pi F d \sin \alpha/c \qquad (10)$$

or:

$$\sin \alpha = c \varphi/2\pi Fd \qquad (11)$$

75
In equation (11) the values of F (or of $\lambda = c/F$) and d
are known with excellent accuracy, but the angle φ
cannot be measured directly: it is only possible to
measure its algebraic value φ_o (smaller than 2π) with
80 a suitable accuracy of the order of one degree, and
whose sign is either that for φ (and thus for α) or the
opposite sign. Measuring φ_o, which is actually a
phase measurement, therefore gives rise to an inde-
terminate factor and does not suffice for a correct
85 evaluation of φ with an accuracy of one degree,
because the absolute value of the angle φ is of the
order of some hundreds to some thousands of
degrees.
    The angle φ may therefore be expressed as a func-
90 tion of φ_o by means of one of the following two for-
mulas:

$$\varphi = \varphi_o + 2k\pi \qquad \text{if } \varphi \text{ is positive} \qquad (12)$$
$$\varphi = \varphi_o - 2k\pi \qquad \text{if } \varphi \text{ is negative}$$
95
where k is a positive integer.
    In order to remove the ambiguity associated with
the measurement of φ_o, it is to be noted that because
F varies during the sawtooth modulation φ will also
100 vary, so that for example between the beginning (φ_1,
F_1) and the end (φ_2, F_2) of the sawtooth:
    $\Delta\varphi = \varphi_2 - \varphi_1$, so that because of formula (10):

$$\Delta\varphi = 2\pi d \sin\alpha (F_2 - F_1)/c$$
105
or:

$$\Delta\varphi = 2\pi d \Delta F \sin \alpha/c \qquad (13)$$
110
or:

$$\sin \alpha = c \Delta\varphi/2\pi d \Delta F \qquad (14)$$
115
$\Delta\varphi$ is an electrical angle which has the sign of α and
which for the envisaged use of the invention rarely
exceeds 2π. It is to be noted that when $\Delta\varphi$ is greater
than 2π, its value can be measured because it con-
120 cerns the variation of the relative phase shifts of the
two signals during a given interval of time which
only comprises a fairly limited number of periods for
the signals Fb_1 and Fb_2.
    For an accuracy of the measurement of $\Delta\varphi$ com-
125 parable to the accuracy obtained for φ_o, that is
approximately one degree, formula (13) yields an
accuracy for $\sin \alpha$ which is less good than formula
(11), as will be seen hereinafter, but on the other
hand this enables $\sin \alpha$ to be determined without
130 ambiguity.

In accordance with the invention the amplitude and sign of the angle $\Delta \varphi$ are now determined, said sign being also that of α and thus of φ because of formula (14) and (11), the value of $\sin \alpha$ is calculated

5 from formula (14), which value is designated $\sin \alpha \Delta \varphi$, said value of $\sin \alpha \Delta \varphi$ is inserted in formula (10) and a first approximated value of the angle φ is calculated therefrom, which is designated $\varphi \Delta \varphi$. On the other hand φ_0 is also measured and is preferably

10 made identical to φ_1. Comparison of the signs of $\Delta \varphi$ and φ_0 makes it possible to decide which of the formulas (12) is valid for the determination of k (φ and $\Delta \varphi$ have the same signs). For example, if the second of these formulas is valid, the value of k is defined as

15 the integer nearest the calculated value, which is equal to $(\varphi_0 - \varphi \Delta \varphi)/2 \pi$. Now φ is calculated in an inverse manner by means of the same formula (12) with which k has been determined, using the integer found for k and, finally, this last-mentioned correct

20 value found for φ is inserted into formula (11), which then enables the value of $\sin \alpha$ and thus the value of α to be calculated with the desired accuracy. Differentiation of formula (10) yields:

25    $d \varphi/d \alpha = 2 \pi Fd \cos \alpha/c$ (15)

which, when assuming for example that: $d = 4m$ and $F = F_1 = 1.22$ GHz, yields:

30   for $\alpha = 0$ $d\alpha = 0.0097 \, d\varphi$
           for $\alpha = 30°$ $d\alpha = 0.0112 \, d\varphi$

that is, an error of $\pm 1°$ for φ corresponds approximately to $0.01°$ for α.

35   Conversely, if α is to be determined from the value of $\Delta \varphi$ only, differentiation of formula (13) yields:

$$d(\Delta \varphi)/d \alpha = 2 \pi \Delta Fd \cos \alpha/c$$

40 or when it is for example assumed that : $d = 4m$ and $\Delta F = 10$ MHz ($F_1 = 1.22$ GHz, $F_2 = 1.23$ GHz):

$$d \alpha = 1.2 \, d (\Delta \varphi)/\cos \alpha \qquad (16).$$

45   In this case the accuracy obtained for α varies from $\pm 1.2°$ for $\alpha = 0$ to $\pm 1.4°$ for $\alpha = 30°$, with an accuracy of $\pm 1°$ for $\Delta \varphi$. Thus, this is clearly insufficient in comparison with the desired accuracy.
It is to be noted that for $d = 4m$ and $F_1 = 1.22$ GHz,

50 the angle φ varies by 2π when α varies by 3.4 degrees at 0° or by 4 degrees at 30 degrees. The accuracy obtained for α by means of formula (16) is therefore sufficient to ensure that the correct value of k can be determined by means of one of the for-

55 mulas (12). If said accuracy is no longer sufficient, this may be solved by increasing the value of d and/or that of ΔF.
An embodiment of the invention, which employs the measuring and calculation method explained in

60 the foregoing, is now described with reference to Figures 3 and 4. In this embodiment the phase shifts are preferably measured by the comparison of counter numbers of clock pulses, the number of pulses being counted between the zero passages of

65 the beat signals Fb_1 and Fb_2.

The instants between the beginning and end of the phase measurement during a sawtooth may be selected arbitrarily, provided that the wavelength or frequency emitted at these two instants is known.

70 The first instant is for example selected to correspond to the beginning of the sawtooth and the second instant to correspond to 90% of the excursion of the sawtooth or: $\Delta F' = 0.9 \Delta F$.
The device of Figure 3 comprises two identical

75 signal-processing chains, whose inputs respectively receive the signal Fb_1 on terminal 15 and the signal Fb_2 on terminal 20. The chain receiving a signal Fb_1 (Fb_2) comprises a cascade of: a shaping circuit 30 (40), which shapes the sinewave signal which it

80 receives into square-wave signals, a synchronizing circuit 31 (41), an AND-gate circuit 32 (42), a period counter 33 (43), and a comparator 34. The outputs of the elements 30, 31 and 32 supply the signals A_1, B_1, C_1, respectively. The signal A_1 (A_2) is supplied

85 directly to a second input of the AND-gate circuit 32 (42). Furthermore, a first (second) output of the comparator 34 is connected to an AND-gate circuit 35 (45), which at a second input receives the signal S from terminal 24 and whose output is connected to

90 a second input of the synchronizing circuit 31 (41). On a third input the circuit 31 (41) receives the signal DE from the terminal 23. The signals B_1 and B_2 are applied to an exclusive-OR gate 50 and to a first switching detector circuit 51. The output of the gate

95 circuit 50, on which the signal E appears, is followed by a cascade of: an AND-gate 52, which receives the output signal of a fast clock generator 53 on the second input and whose output supplies a signal H, a pulse counter 54, a memory 55, a computing ele-

100 ment 56 for calculating $\Delta \varphi$, $\sin \alpha \Delta \varphi$, $\varphi \Delta \varphi$, k, φ, $\sin \alpha$ and α and a display element 57 for displaying th value of α. The circuit 51, whose function it is to determine the signs of the measured phase shifts, transfers said sign, for example in the form of logic

105 levels, to the memory 55 via two conductors. Moreover, the computing element 56 receives in digital form, the value of the distance d, which is displayed by an element 58, and the value of the transmitted frequency F (or the wavelength λ) which

110 is transferred to terminal 25 at the instants (t_1, t_2) which respectively correspond to the transition to the high level of the logic signals DE and S, which in Figure 1 is indicated by the conductors which connect each of the terminals 23 and 24 to a control

115 input of the analog-to-digital converter 22.
The operation of the apparatus of Figure 3 is described hereinafter with reference to Figure 4, which is a time diagram of the signals EM, DE, S, Fb_1, A_1, B_1, C_1, Fb_2, A_2, B_2, C_2, E, H. In Figure 4 the signal G

120 is a fixed frequency threshold, determined by the element 21 of Figure 1, for example equal to 90% of the peak value of the sawtooth ($\Delta F' = 0.9 \Delta F$) and S is a logic signal which changes from 0 to 1 when the threshold G is reached and which returns to 0 at the

125 end of the sawtooth.
The phase shift between the echo signals received by the antennas 3 and 4 is imparted to the beat signals of the frequencies fb_1 and fb_2 by means of mixers 10 and 16 (Figure 1), said signals being available in

130 the form of a continuous sinewave on the terminals

15 and 20 (Figure 1), in which form they are shown in
Figure 4. By means of the circuits 30, 40 (Figure 3)
the signals Fb₁ and Fb₂ are shaped into squarewave
signals A₁, A₂ whose amplitude is adapted to suit the
5 following logic circuits (logic levels "0" and "1").
The synchronizing circuit 31, 41 has an output B₁, B₂,
which is 0 between the sawtooth waves and which
becomes 1 upon the first change from 0 to 1 of the
signal A₁ or A₂ following the instant t₁, that is for
10 example the beginning of the sawtooth. For this
purpose, said synchronizing circuit 31, 41 receives
the signal DE on its third "start" input. When, at the
instant t₂, it receives a signal on its second "stop"
input, either B₁ or B₂ will return to 0 upon the first
15 transition from 0 to 1 of the signal A₁ or A₂ following
said instant. Such logic circuits 31, 41 are known to
those skilled in the art. The AND gate 32 or 42, which
receive the signals A₁ and B₁ or A₂ and B₂, produces
an integral number of periods C₁ or C₂ on its output
20 (an increasing number N₁ or N₂). The counter 33 or
43 therefore supplies a number equal to the number
of sinewave periods of Fb₁ or Fb₂ during the interval
under consideration. When the signal S passes to
the 1 level in order to allow the signal B₁ (or the
25 signal B₂) to be reset to zero via the AND-circuit 35 or
45, one of the two following modes of operation of
the apparatus is possible.
1) N₂ ⩾ N₁, (case considered in Figure 4), in which
case the comparator 34 transfers a logic "1" via the
30 AND-gate 45, which resets the output B₂ of the gate
circuit 41 to zero during the following passage from
0 to 1 of the period A₂. The AND-gate circuit 35
remains closed (inhibited) until N₁ = N₂. At this
instant the first output of the comparator 34 also
35 goes to 1, which pulls the synchronizing circuit 31 to
0 via the gate circuit 35. The AND-gate circuits 42 and
32 thus have supplied the same number of periods
and the durations of the "1" levels of the signals B₁
and B₂ represent the respective durations of the
40 same number of sinewave periods in the two respec-
tive signal processing chains Fb₁ and Fb₂.
2) N₂ < N₁, in which case the operations in the two
chains described in the foregoing are interchanged,
and by means of the same reasoning the same result
45 is obtained as in the preceding paragraph.
The signals B₁ and B₂ are, for example, as shown in
Figure 4, but other configurations are also possible
because first either B₁ or B₂ switches from the low
level to the high level (first and second switching
50 operation) and subsequently either B₁ or B₂ changes
from the high level to the low level (third and fourth
switching operation).
The sign of φ₀ depends on the chronological sequ-
ence of the first and the second switching operation.
55 By covention, it is for example decided to count φ₀
positively when the first switching operation takes
place in the first signal processing chain and nega-
tively if this takes place in the second chain. This
convention, as will be seen hereinafter, allows the
60 value of α to be determined in a trigonometric sense.
In accordance with this convention the angle φₙ is
negative in Figure 4.
On the other hand, the difference between the
durations of the high levels of the signals B₁ and B₂
65 represents the absolute value of the relative overall

phase shift Δφ. The absolute value and the sign of Δ
φ can be obtained by algebraically measuring φ₀',
that is, the algebraic difference between the falling
edges of the signals B₁ and B₂ (third and fourth
70 switching operations) with the same sign conven-
tion as in the foregoing and by subtracting the algeb-
raic value obtained for φ₀ from said algebraic value
(first and second switching operations), which rule is
valid regardless of the configuration of the signals B₁
75 and B₂. The sign obtained for Δφ is also the sign of α
owing to formula (14).
In Figure 4 the two measured phase shifts are
negative, their difference (the second one minus the
first one) is negative, which means that the angle α is
80 negative when the axis oz is taken as the reference
(which case is represented in Figures 1 and 2). It is to
be noted that Figures 1, 2 and 4 represent the same
case, for which the following inequality is valid: Fb₂
> Fb₁. If the beat frequency Fb₁ is maintained con-
85 stant and equal to a predetermined value, for exam-
ple 25 kHz (period of 40 μs), if B₁ has a delay of 10 μs
at the beginning and of 20 μs at the end, then:

– The initial phase shift φ₀ is: $2\pi(-10/40) = -\pi/2 =$
90    $-90°$
– The final phase shift φ₀' is: $2\pi(-20/40) = -\pi =$
    $-180°$
– The variation of the phase shift Δφ is conse-
quently: $(-\pi) - (-\pi/2) = -\pi/2 = -90°$.
95

When the variation of the transmitted frequency, on
terminal 25, between the beginning and the end of
counting is known, that is, $F_2 - F_1$, the value of sin α
can be calculated from said variation in a first
100 approximation (accuracy of the order of one degree
for arc sin α).
The actual circuit for measuring and calculating α
from time measurements representing the phase
shifts φ₀ and Δφ is shown in the right-hand part of
105 Figure 3 (the elements 50 to 58).
The exclusive-OR gate circuit 50 receives the two
signals B₁ and B₂ and supplies the signal E (Figure 4),
which for a given sawtooth comprises two pulses
representing the initial and final phase shifts φ₀ and
110 φ₀'. Via the AND-gate circuit 52, which also receive
the output signal of the fast clock generator 53, the
signal E is converted into a counting pulse signal H
with a frequency of, for example, 20 MHz. At the end
of each train of pulses supplied by the AND-gate 52
115 the counter 54, which has been reset to zero before
the beginning of each pulse train, by means not
shown, provides the phase-shift value expressed by
a number which is a measure of the time which has
elapsed between similar changes of the signals B₁
120 and B₂.
The circuit 51 detects which circuit each time
effects the first switching operation and, in accor-
dance with the convention adopted derives there-
from a + or – sign, which is subsequently transfer-
125 red in the form of logic signals.
At the end of the counting operation at 54 the
number and sign are stored at 55, which is suitably a
temporary-storage memory, for example a buffer
memory. Said digital values are subsequently
130 transferred to the computing element 56, which is

suitably a microprocessor. As indicated in the fore-
going, the element 56 also receives, in digital form,
the value of the frequency F or the wavelength of the
transmitted signal as well as th value of the dis-
5 tance d from the element 58. In a chronological
sequence the operations or calculations effected for
each sawtooth by 56 are the following:
— making the first algebraic value from the memory
55 equal to φ_0 and the second algebraic value to φ'_0;
10 — calculating $\Delta \varphi$ by forming the difference between
φ'_0 and φ_0;
— calculation of sin α from formula (14) (sin $\alpha \Delta \varphi$);
— calculation of $\varphi \Delta \varphi$ from formula (10);
— selection of the formula (12) to be used as a func-
15 tion of the respective signs of φ_0 and $\Delta \varphi$;
— the approximated calculation of k from the approp-
riate formula (12) and determining k;
— calculation of φ from the same formula (12) using
the integral value of k;
20 — calculation of sin α from formula (11);
— calculation of α as a function of sin α.
The value of α thus determined is transferred to
the element 57, which suitably displays said value in
digital form, for example in degrees and minutes or
25 hundredths of degrees, with the aid of light emitting
diodes or liquid crystals.
It is to be noted that the foregoing calculation of φ
$\Delta \varphi$ may be simplified because, except for clarity of
the explanation it is not necessary to include the
30 approximated value of sin α, that is sin $\alpha \Delta \varphi$. Combin-
ing formulas (14) and (10) namely yields:

$$\varphi = F \Delta \varphi / \Delta F$$

35 or:

$$\varphi \Delta \varphi = F_1 \Delta \varphi / (F_2 - F_1) = F_1 (\varphi'_0 - \varphi_0)/(F_2 - F_1)$$

in which formula now only the values of F_1, F_2, φ_0 and
40 φ'_0 occur, i.e. the actual measuring values. As
regards the accuracy which is obtained, it is to be
noted if the absolute error is the same for $\Delta \varphi$ and φ
after accurate calculation of the latter, the ratio

45
$$\frac{\Delta F}{F}$$

enables the relative error for $\Delta \varphi$ to be maintained for
φ using the last-mentioned formulas, so that the high
50 accuracy obtained for φ can is maintained in the
accuracy obtained for α.
In another embodiment of the invention, not
shown, the accuracy obtained for the value of α may
be further improved from a few hundredths of a
55 degree to approximately one hundredth of a degree
in the example where an accuracy of one degree for
the phase shift measurements is obtained. In this
embodiment the phase shifts of a plurality of pairs of
sinewave periods of the signals Fb_1 and Fb_2 are
60 measured by each time taking the corresponding
value of the frequency (or wavelength) of the trans-
mitted wave and assigning, to each value of φ_0 thus
obtained, the same angular value φ'_0, which is
determined by the falling edges of the signals B_1 and
65 B_2. Thus, by means of the computing element it is

possible to determine for each sawtooth as many
values of sin α as the number of different values
measured for the angle φ_0 and of the frequency F_1
corresponding thereto, each time taking the same
70 value for φ'_0 and for F_2. In this case the computing
element should perform an additional operation of a
different nature, which for determining α consists in
previously determining the mean of the different
values found for sin α.
75 Suitably, the antennas 2, 3 and 4 shown in Figure 1
are of the directional type and cover an angular sec-
tor of the order of 60 degrees. However, they may
cover a larger angle, for example of approximately
120 degrees, but when determining the angle α this
80 may result in a smaller accuracy than in the case of a
coverage of 60 degrees. The arrangement of six
devices as described in the foregoing at 60 degrees
from each other or of three devices at 120 degrees
from each other, depending on whether the angle of
85 coverage of the antennas is for example 60 or 120
degrees, makes it possible to cover the entire plane.
CLAIMS
1. A method of determining the azimuth α of a
radiowave transponder relative to a radar system,
90 which system transmits a wave whose frequency F is
a linear function of time, said radar system compris-
ing a transmitting antenna and two receiving anten-
nas, which are located at a distance d from each
other, and supplying two beat signals Fb_1 and Fb_2
95 having a frequency fb_1 and fb_2 respectively, which
are obtained by mixing the transmitted wave and the
echo wave received from said transponder on each
of the two receiving antennas, characterized in that
the said method comprises at least the following
100 steps:
— The algebraic measurement of the phase shift φ_0
between the signals Fb_1 and Fb_2 and the measure-
ment of the frequency F_1 at a predetermined, arbit-
rarily chosen first instant t_1,
105 — The algebraic measurement of the phase shift φ'_0
between the signals Fb_1 and Fb_2 and the measure-
ment of the frequency F_2 at a second arbitrarily
chosen instant t_2, $\varphi'_0 - \varphi_0$ being such that the
number of sinewave periods of fb_1 and fb_2 b tween
110 the two instants t_1 and t_2 is substantially the same,
— The calculation of a relative overall phase variation
$\Delta \varphi$ which may be greater than 2π between the
instants t_1 and t_2, by determining the difference
between φ'_0 and φ_0,
115 — The approximated calculation of φ, which is the
overall phase shift between the signals Fb_1 and Fb_2
at said first instant t_1, to be reckoned from the fre-
quency F at which said overall phase shift is zero,
as a function of F_1, F_2 and the value of $\Delta \varphi$ found in
120 the preceding step, that is $\varphi \Delta \varphi$,
— The determination of the maximum angle 2k π, k
being a positive integer which is actually contained
in the angle φ, from φ_0, $\varphi \Delta \varphi$ found in the preced-
ing step and of the respective signs of φ_0 and of Δ
125 φ,
— Making φ identical to the sum: $\varphi_0 + 2k \pi$ or $\varphi_0 - 2k$
π depending on the respective signs of φ_0 and of Δ
φ,
— The calculation of sin α from the values of F_1, d and
130 the exact value of φ found in the preceding step,

- The calculation of α from the value of $\sin \alpha$ obtained in the preceding step,
- The display of the value of α found in the preceding step.

5   2.   A method of determining α, as claimed in Claim 1, characterized in that said method in addition comprises the following steps:
- the algebraic measurement of the phase shift $(\varphi_0)_i$ between the signals Fb_1 and Fb_2 and the measure-
10   ment of the corresponding frequency F_i at a plurality of instants t_i which precede said instant t_2,
- determining each angle α_i from the values F_1, F_2, $(\Delta \varphi)_i = \varphi'_0 - (\varphi_0)_i$, k_i, $(\varphi_0)_i$, d,
- determining the angle α which is equal to the mean
15   values of the angles α_i determined in the preceding step.

3.   An apparatus for measuring the azimuth α using the method as claimed in Claim 1 or 2, which apparatus forms part of a radar system which
20   transmits a high frequency continuous wave, which is frequency modulated with a sawtooth having a constant frequency sweep ΔF and a duration T, and which simultaneously receives the previously transmitted wave which is reflected by a transpon-
25   der, said radar system supplying a signal Fb_1 of a first beat frequency fb_1, obtained by mixing the transmitted signal of the instantaneous frequency F and the signal received on a first receiving antenna, and a signal Fb_2 of a second beat frequency fb_2,
30   obtained by mixing said transmitted signal of the frequency F and a signal received on a second receiving antenna, the reference direction for measuring the azimuth α of said transponder being the mid-perpendicular to the line of length t at whose
35   ends said receiving antennas are located, characterized in that it comprises:
- First means for shaping said signals Fb_1, Fb_2 of the frequency fb_1 and fb_2 so to obtain squarewave signals of the same phase and the same frequency,
40   - Second means for measuring the phase shift φ_0 between the squarewave signals of frequency fb_1 and fb_2, as well as the frequency F for at least one point of said sawtooth,
- Third means for determining at least two trains of
45   squarewave signals having the same number of periods and whose starting points differ by at least one period,
- Fourth means for measuring the overall relative phase variation $\Delta \varphi$ between the beginning, at the
50   instant t_1 for a frequency F_1, and the end, at the instant t_2 for a frequency F_2, of said trains of squarewave signals,
- Fifth means for calculating the angle α from the values of F_1, F_2, d, φ_0 and $\Delta \varphi$ and for displaying
55   said angle.

4.   An apparatus for measuring the azimuth as claimed in Claim 3, characterized in that the duration T of the sawtooth is fixed.

5.   An azimuth measuring apparatus as claimed
60   in Claim 3, characterized in that the duration T of the sawtooth is variable as a linear function of the distance between said radar system and said transponder owing to a control loop for the transmitted wave, which maintains one of the frequencies fb_1 or fb_2
65   substantially constant and equal to a fixed fre-

quency.

6.   An azimuth measuring apparatus as claimed in any of the Claims 3, 4 or 5, characterized in that said point of the sawtooth has the time t_1 and the
70   frequency $F_0 = F_1$ as coordinates.

7.   An azimuth measuring apparatus as claimed in any of the Claims 3, 4 or 5, characterized in that it comprises means for measuring the phase shift $(\varphi_0)_i$ and the frequency F_i for a plurality of points of the
75   sawtooth, at instants t_i later than or equal to t_1 and prior to t_2.

8.   An azimuth measuring apparatus as claimed in any one of the Claims 4 to 7, characterized in that said second means for measuring the phase shift φ_0
80   comprise, for each of the signals Fb_1 and Fb_2, a synchronizing circuit, which receives the output signal A_1 (or A_2) from said first shaping means, which on a third input receives a first control signal DE derived from the sawtooth and which supplies a logic signal
85   B_1 (or B_2), and an exclusive -OR-gate circuit and a circuit for detecting the first switching operation, which last-mentioned circuits each receive the signals B_1 and B_2, the output of said exclusive OR-gate circuit being connected to the cascade of an AND-gate cir-
90   cuit, receiving the output of a fast clock generator on its second input, a pulse counter and temporary-storage memory, which also receives the output signal of said circuit for detecting the first switching operation.

95   9.   An azimuth measuring apparatus as claimed in Claim 8, characterized in that said third means for determining at least two trains of squarewave signals having the same number of periods for each of the signals Fb_1 or Fb_2 comprise a first AND-gate cir-
100   cuit, which receives the signals A_1, B_1 (or A_2, B_2), which gate circuit is connected to a period counter, which in its turn is connected to a comparator whose respective output is connected to a second AND-gate circuit, which on a second input receives a second
105   control signal S derived from the sawtooth, and which supplies a second control signal to a second input of said synchronizing circuit.

10.   An azimuth measuring apparatus as claimed in Claims 8 and 9 in combination, characterized in
110   that said fourth means are constituted by the combination of said second means and third means.

11.   An azimuth measuring apparatus as claimed in any one of the Claims 3 to 10, in which said second means for calculating and displaying the angle α are
115   constituted by a microprocessor.

12.   A method of determining azimuth substantially as herein described with reference to equations (1) to (15).

13.   An azimuth measuring apparatus substan-
120   tially as herein described with reference to the accompanying drawings.